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The empirical white dwarf cooling sequence

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Abstract. White dwarf stars cool as they age, hence they can be used as chronometers for various stellar systems. Their value as clocks depends critically on how well we understand the physics of cooling. In this contribution we outline how to derive an empirical cooling sequence and then compare it with a standard white dwarf cooling model. Some differences are noted suggesting that there is still missing physics in the models. A more detailed version of this communication can be found in Goldsbury et al. (2012).

Key words. Stars: white dwarfs – Stars: globular clusters

1. Introduction

About 95% of all stars ever formed will end their lives as white dwarfs. For this reason alone we should strive to understand their formation and subsequent evolution. In addition, they turn out to be rather useful as cosmic clocks. Since there are no appreciable nuclear reactions in the later stages of white dwarf evolution, their photon luminosity comes largely from the cooling of the non-degenerative ions together with some contribution from a slow gravitational contraction, mainly of the outer parts of the star. In hot white dwarfs, neutrinos carry off an appreciable amount of energy and these losses can dominate for very hot objects. The non-degenerate atmosphere of the star acts like a blanket slowly releasing energy, the rate of release being controlled by the opacity in the atmosphere. The basic ideas regarding cooling were first formulated by Mestel (1952) and led to an extremely simple relationship, namely that the surface temperature of a white dwarf should decrease with time as temperature $\propto$ time$^{-0.4}$. This expression has stood the test of time remarkably well. However, equally remarkable is that the rate of white dwarf cooling has never been critically tested for the hotter stars: we concentrate on this here.

2. Approach to testing basic white dwarf cooling theory

An empirical test of the rate of cooling of white dwarfs has within it several components. Clearly the test should in no way involve the cooling models themselves – only after an empirical sequence has been established should the existing theoretical models be invoked and the comparison carried out. The sample of white dwarfs should be as large and as homogeneous as possible. Preferably this means that the sample of white dwarfs should all be of about the same mass, all at the same distance in order to avoid measuring individual distances (and reddenings) which could be fraught with error, of a range of ages and temperatures, and have evolved from main sequence stars of the same metal abundance to avoid complications involving any metallicity dependence in the initial–final mass relation of the white dwarfs. All these criteria point to using a sample of white dwarfs in a populous star cluster. In fact, given the need for a large sample, the cluster of choice would naturally be a globular cluster.

3. The data

Because a large homogeneous sample of white dwarfs is required to construct an empirical cooling sequence we used our Hubble Space Telescope data set in 47 Tuc (GO–11677). Details about these data and the reductions can be found in Kalirai et al. (2012).

4. Constructing the empirical white dwarf cooling sequence

The process used in constructing the cooling sequence is as follows:

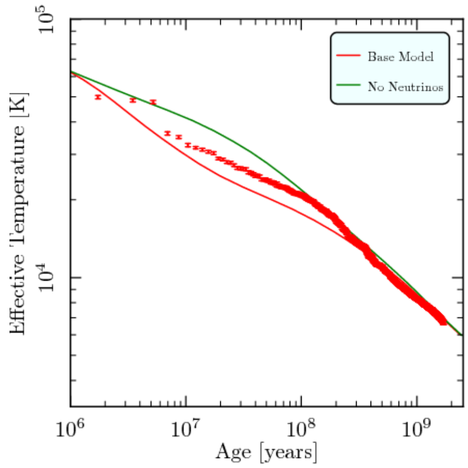

Fig. 1. The empirical white dwarf cooling sequence (points with error bars) compared with theoretical models using the MESA code (Paxton et al. 2011).

- The white dwarf sample is isolated in the cluster colour-magnitude diagram. In our case we identified almost 1000 white dwarfs in our 47 Tuc fields.
- The photometry for each white dwarf is converted to temperature using the spectral models of Tremblay et al. (2011). Corrections for distance and reddening are applied to the spectral models.
- The stars are sorted by temperature, the hottest star being number 1, second hottest number 2, etc.
- The white dwarfs are all assumed to be of the same mass. This is not unreasonable considering that we are interested only in young white dwarfs in this analysis.
- The reasonable assumption is then made that stars are leaving the main sequence at a uniform rate. We determine this rate by isolating a sample of red giant stars in our field and use stellar evolution models to establish a time scale for a star to evolve over the range in magnitude covered by these red giants. We then divide the number of giant stars in the CMD by the evolutionary timescale to get the rate at which stars are leaving the main sequence. These are the only evolutionary models used in constructing the white dwarf cooling se-

quence, but note they are giant models not white dwarf cooling models. In addition, evolutionary timescales in these giant models are not terribly sensitive to metallicity (Dartmouth Stellar Evolution Online Calculator).

- The rate at which stars are leaving the main sequence is then multiplied by the ranking of each white dwarf and this then produces an evolutionary time as a white dwarf. Coupling this with the temperature of the star produces the empirical white dwarf cooling sequence.

5. The cooling sequence

The cooling sequence as derived in the previous section is plotted in Fig. 1. The red points with error bars are the data while two theoretical models are shown. The red model is a standard white dwarf cooling model including all the currently understood input physics. These models were derived using the publicly-available MESA evolutionary code (Paxton et al. 2011). The theoretical cooling sequence produced by this code is similar to others in the literature (Fontaine et al. (2001), Hansen (2004), Lawlor and MacDonald (2006), and Renedo et al. (2010)). All models exhibit a linear region (in log-log space) at high temperatures with a slope near -0.2, followed by a transition region and then a steeper slope near -0.4 (the Mestel value) below a temperature of about 15,000K. The empirical cooling curve is similar except that its transition is at a considerably hotter temperature of about 20,000K. In addition, the transition to Mestel cooling is much more abrupt in the empirical curve than it is in the models.

To gain further physical insight into the possible differences between the models and the data, we developed a cooling curve where the neutrino emission was turned off. We are not suggesting that neutrino emission does not occur in the interior of a white dwarf, but rather this straw-man model is used to see what suppressing a known source of energy loss does to the models. Neutrino emission is known to dominate the luminosity of white dwarfs at high temperature (≥ 20,000K).

The model without neutrinos (green curve in Fig. 1) appears to be a better fit at least over the temperature range 20,000K to 15,000K. This may be suggesting that there is a heat source in these stars that is not accounted for in the models or that some other parameters such as the thickness of the atmosphere, the atmospheric opacity or convection are not being modeled correctly. Hopefully this empirical cooling sequence will be used by the modelers to try and improve the input physics in their calculations.

6. Conclusions

White dwarfs are increasingly being used in cosmochronology, that is in the dating of various systems in the cosmos. The white dwarf cooling curve is the critical tool here and our empirical sequence seems to imply some missing physics in all the existing models at high temperature. This discrepancy is not likely very important if cool, old white dwarfs are the major objects involved in the dating, for example as in the determination of the age of a globular star cluster or the Galactic halo or thick disk. But in young star clusters and binaries containing hot white dwarfs, it is critical to understand why this empirical cooling sequence does not fit the current generation of theoretical models.

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